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PARAMETER AND LUMINOSITY SCENARIOS FOR FCC-hh

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Abstract

In preparation for the 2026 Update of the European Strategy for Particle Physics, various options are being proposed for a future circular hadron collider, FCC-hh. Here, we discuss a few operational scenarios spanning c.m. energies from about 70 TeV to 120 TeV, which correspond to the arc dipole field strengths ranging from 12 T to 20 T. We present the respective integrated luminosity forecasts, considering a proton beam current similar to the one of the existing LHC (0.5 A) or the upcoming HL-LHC (1.1 A), and limiting the total synchrotron radiation power to at most 5 MW. Additional constraints are imposed on the beam-beam tune shift and the maximum event pile-up.

INTRODUCTION

For the present layout of the FCC, and after a meticulous optimisation of the bending-magnet filling factor [1, 2], the nominal dipole field of 14 T, reachable with Nb_3Sn conductor, provides a centre-of-mass (c.m.) energy close to 85 TeV. The use of 17 T dipoles, based on high-temperature superconductors (HTS), would provide a c.m. energy slightly in excess of 100 TeV. With 20 T magnets, also based on HTS technology, a c.m. energy of 120 TeV could be achieved. Lowering the dipole field to 12 T (not far above the 11.4 T peak field of the HL-LHC Nb_3Sn quadrupole magnets), the c.m. energy would be 72 TeV.

The nominal beam current of FCC-hh is 0.5 A (~ 10^{11} protons per bunch at 25 ns spacing), as was also considered for the 2018 FCC-hh [3]. At a c.m. energy of 100 TeV, for this beam current, we reach a total synchrotron radiation power of 5 MW, which must be removed from the cold magnets. We consider this to be the maximum value tolerable. Therefore, going to even higher energies requires a reduction of the beam current to respect the above power limit. However, if the beam energy is decreased, one can hold either the synchrotron-radiation power or the beam current constant.

The following six scenarios represent well-defined discrete and distinct options for the FCC-hh:

- A machine based on 14 T dipoles and 0.5 A current (F14), which is the baseline scenario for the 2025 FCC Feasibility Study report [4].
- A machine based on 12 T dipoles, with the same beam current of 0.5 A (F12LL).
- A machine based on the same 12 T technology close to deployment, but with a higher beam current of 1.1 A, as considered for the HL-LHC (F12HL).
- The same case as F12HL but limiting the pile up not to exceed a value of 1000 (F12PU).
- A machine based on HTS dipole magnets with a field of 17 T, just exceeding 100 TeV c.m. energy, and still considering a beam current of about 0.5 A with a total synchrotron radiation power at the 5 MW limit (F17).
- A machine, also based on HTS dipole magnets, but with a field of 20 T, and limiting the beam current to 0.25 A, so that the synchrotron-radiation power remains 5 MW (F20).

We will next elaborate on the collider parameters for these six cases.

MAIN COLLIDER PARAMETERS

The options outlined in the previous section are detailed in Table 1, which compiles the main machine and magnet parameters. The figures reported there are a combination of results from the literature, and scaling applied to such options. For this discussion, we only report the required dipole field. It is clear that a complete analysis of any option would require devising quadrupoles and dispersion suppressor magnets, as well as adapted insertions. Indeed, simple scaling does not necessarily produce consistent and feasible configurations, as the optics for the different energy options may differ considerably. Still, in spite of the simple approach taken here, our basic considerations suffice to provide a rough perspective of different FCC-hh scenarios.

In Table 1, the c.m. collision energy increases in proportion to the arc dipole field. All columns assume a radio frequency (rf) of 400 MHz, a nominal bunch spacing of 25 ns, and 160 days of allocated physics run time per year.

It is natural to assume high-luminosity collisions in $n_{\rm IP} = 2$ primary interaction points (IPs), and possible lower-luminosity secondary collisions at two other IPs, as for the LHC and HL-LHC. We take the total number of bunches $n_{\rm b}$ to be 9450, scaling from the LHC (HL-LHC) with the length of the circumference. Note that higher beam energies will require a revision of the dump and injection kicker system, which may have an impact on the maximum number of bunches allowed.

The FCC-hh optics for a c.m. energy of 84.6 TeV achieved an interaction point (IP) beta function β^* of 0.30 m. We extrapolate around this value by keeping the initial beam size (i.e. the beam size prior to any radiation damping) at the interaction point and in the final quadrupoles constant, which implies $\beta^* \propto \gamma$, where $\gamma = E_{\rm b}/(m_p c^2)$ denotes the relativistic Lorentz factor, with $E_{\rm b}$ the beam energy, m_p the proton mass and c the speed of light.

We assume that FCC-hh uses crab cavities to compensate for the effect of the needed crossing angle.

The initial luminosity is given by

$$L_0 = f_{\rm rev} n_{\rm b} N_b^2 / \left(4\pi \sigma_{x,y}^{*\,2}\right) , \quad (1)$$

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where $f_{\rm rev}$ denotes the revolution frequency, and $\sigma^*_{x,y} = \sqrt{\beta^*\varepsilon_{\rm n}/\gamma}$ the rms beam size at the IP ($\varepsilon_{\rm n}$ being the normalised emittance value), assuming round beams ($\sigma^*_y = \sigma^*_x$).

The total and inelastic proton-proton cross sections, $\sigma_{\rm tot}$ and $\sigma_{\rm inel}$, are weakly dependent on the collision energy, as indicated by Eqs. (6) and (7) in Ref. [5], which are based on Refs. [6–11]. The total cross section $\sigma_{\rm tot}$ increases from about 111 mb at 14 TeV (LHC) to 160 mb at 120 TeV c.m. energy (F20), the inelastic cross section $\sigma_{\rm inel}$ from 85 mb to 113 mb. The inelastic cross section roughly relates to the number of events per bunch crossing recorded in the detector (the so-called event pile up), as

$$n_{\rm event} = \sigma_{\rm inel} L_0 / \left(n_{\rm b} f_{\rm rev}\right) \ . \quad (2)$$

The initial pile up varies between 600 and 3000 events per bunch crossing for the FCC-hh versions considered. With perfect crab crossing and for Gaussian bunch profiles, the rms extent of the luminous region is equal to the rms bunch length divided by $\sqrt{2}$.

The total cross section $\sigma_{\rm tot}$ determines the initial proton burn-off time $\tau_{\rm bu}$ as

$$\frac{1}{\tau_{\rm bu}} = -\frac{\dot{N}_{\rm b}}{N_{\rm b}} = \frac{\sigma_{\rm tot} L_0 n_{\rm IP}}{N_b n_{\rm b}} \ . \quad (3)$$

The energy stored per beam scales exactly with the beam energy and the beam current, and for the 14 T case it is close to 7 GJ, about 10 times higher than for the HL-LHC.

The proton energy loss per turn due to synchrotron radiation increases as the fourth power of the beam energy, reaching 10.1 MeV for F20, to be compared with 6.7 keV at the LHC.

For constant beam current and bending radius, the total synchrotron-radiation power also increases as the fourth power of energy. While for the nominal LHC, the SR power of one beam is 3.6 kW, for F17 and F20 it reaches 2.5 MW per beam, or about 5 MW in total, and the synchrotron radiation per unit length assumes values around 33 W/m per aperture. This SR heat can still be removed from inside the arcs with the FCC-hh beam-screen design. As stated, for F17 and F20, the heat load from synchrotron radiation limits the maximum beam current.

The radiation damping time scales as $\rho^2 E_b^{-3}$, where ρ denotes the dipole bending radius. The interplay of proton burn-off and radiation damping determines the optimum physics run time (i.e. the moment the two beams are dumped for a new injection) as a function of the average turnaround time (the time between the dump and the start of the new physics fill).

For all FCC-hh scenarios, the initial proton burn-off time, of a few hours, is longer than, or at least equal to, the transverse emittance damping time, of the order of half an hour. As a result, both the luminosity and the beam-beam tune shift increase with time in store, and for the latter we must assume a maximum acceptable value, which, once reached, is maintained by controlled emittance blow-up through transverse noise excitation [5]. The time evolution of the luminosity and the optimum run length $t_{\rm r}$ for most scenarios then follows from Eqs. (33)–(54) in Ref. [5]. In cases F12LL and F12HL, the maximum beam-beam tune shift of 0.025 is never reached. For these two cases, the optimum run length follows from Eq. (5) in Ref. [12].

For the purpose of illustration, we conservatively consider a maximum beam-beam tune shift of 0.025, which is slightly lower than the value of 0.03 previously assumed for the "phase 2" of the FCC-hh [3, 5]. For the average turnaround time and for the number of physics days per year, we adopt the canonical values of Ref. [13] (5 hours and 160 days). The ideal integrated luminosity per day is then calculated for the optimal running time $t_{\rm r}$ and the assumed average turnaround time. The ideal evolution of instantaneous luminosity during 24 h is shown in Fig. 1, for all six FCC-hh versions. The increase in instantaneous luminosity during the early store for F12LL, F14, and F17 also is a measure of the increase of the event pile up from its initial value, which is of the order of 50%. The ideal integrated luminosity accumulation for the same six scenarios is illustrated in Fig. 2.

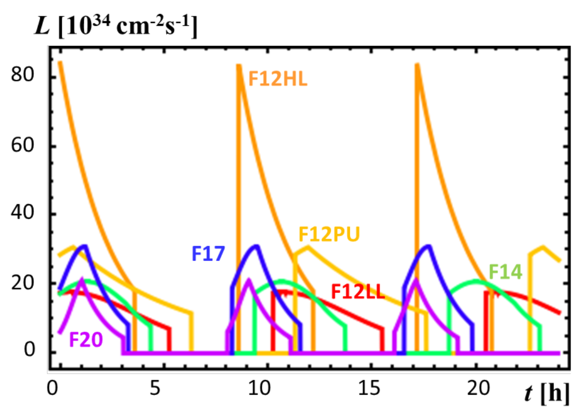

Figure 1: Instantaneous luminosity as a function of time during 24 hours for various options with 25 ns bunch spacing and a maximum total beam-beam tune shift of 0.025.

The luminosity delivered per year is finally obtained by multiplying the latter by the number of physics days scheduled and the postulated availability of 70% [13], which is slightly lower than for the LHC and HL-LHC.

Finally, lowering the synchrotron radiation power by reducing the number of bunches in order to restrict the total power consumption of the future FCC-hh, would decrease the peak and integrated luminosity by the same factor.

ADVANCED OPTIONS

A possible staging scenario for FCC-hh to reduce initial cost could consist in starting with a lower field of, e.g. 12 T (or less) for the complete ring, and then replacing all dipoles by higher field, e.g. 20 T magnets.

Hadron beam top-up injection would offer higher efficiency and much higher integrated luminosity. This would also allow reducing the power consumption (namely, both

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Table 1: Key parameters of six FCC-hh options compared with HL-LHC under similar assumptions [5, 13]‡ and LHC, for operation with proton beams. All values refer to the collision energy. The FCC-hh ring circumference is 90.7 km.

Parameter	Unit	F12LL	F12HL	F12PU	F14	F17	F20	(HL-)LHC
Centre-of-mass energy	TeV	72	72	72	85	102	120	14
Peak arc dipole field	T	12	12	12	14	17	20	8.33
Beam current	A	0.5	1.1	1.1	0.5	0.5	0.25	(1.12) 0.58
Bunch population	10^{11}	1.0	2.2	2.2	1.0	1.0	0.4	(2.2) 1.15
Bunches / beam		9450						(2760) 2808
Rf voltage	MV	30	30	30	35	43	50	(16) 16
Momentum compaction	10^{-4}	1.5						(3.22) 3.22
RMS bunch length	mm	~ 80						(90) 75.5
Bucket half height	10^{-3}	0.17	0.17	0.17	0.16	0.16	0.14	0.36
RMS momentum spread	10^{-4}	0.57	0.57	0.57	0.57	0.57	0.57	1.129
Longit. emit. ($4\pi\sigma_z\sigma_E$)	eVs	6.9	6.9	6.9	8.1	9.7	11.4	2.5
Norm. tr. rms emittance	µm	2.5						(2.5) 3.75
IP beta function $\beta^*_{x,y}$	m	0.22	0.22	0.65	0.26	0.31	0.37	(0.15) 0.55
Initial IP beam size $\sigma^*_{x,y}$	µm	3.8	3.8	6.5	3.8	3.8	3.8	(7.1 min.) 16.7
Initial luminosity / IP	$nb^{-1}s^{-1}$	174	840	284	171	188	60	(50, levelled) 10
Total cross section	mb	148	148	148	151	156	160	111
Inelastic cross section	mb	105	105	105	107	110	113	85
Initial events / crossing		580	2820	955	590	660	218	(135) 27
RMS luminous region	mm	~ 57						(64) 45
Stored energy / beam	GJ	5.4	12.0	12.0	6.4	7.3	4.5	(0.7) 0.36
Energy loss / p / turn	MeV	1.3	1.3	1.3	2.4	5.3	10.1	0.0067
SR power / beam	kW	650	1450	1450	1200	2500	2500	(7.3) 3.6
SR power / length	W/m/ap.	8.4	18.8	18.8	15.6	32.5	32.5	(0.33) 0.17
Transv. emit. damp. time	h	2.3	2.3	2.3	1.5	0.8	0.5	25.8
Initial proton burn-off time	h	5.1	2.3	6.9	5.1	4.0	8.4	(15) 40
Average turnaround time	h	5						4 (5)
Optimum run time	h	5.3	3.6	6.3	4.4	3.3	3.0	(18–13) ~10
Accelerator availability	—	70%						(80%) 78%
Ideal luminosity / day	fb^{-1}	7.1	16.6	10.7	7.8	7.3	3.8	(1.9) 0.4
Luminosity / yr	fb^{-1}	790	1860	1200	870	815	425	(240) 55

‡The latest official HL-LHC parameters can be found in Ref. [14].

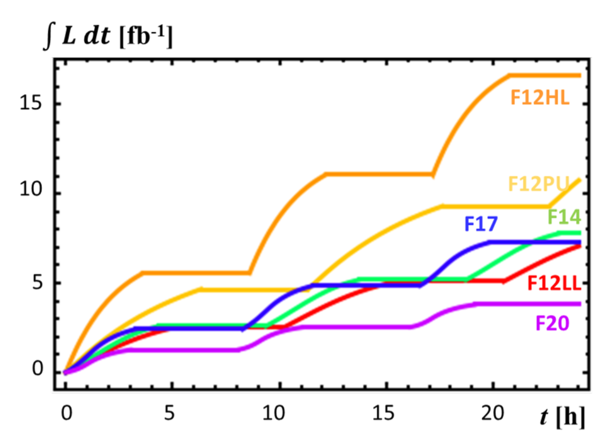

Figure 2: Integrated luminosity as a function of time during 24 hours for various options with 25 ns bunch spacing and a maximum total beam-beam tune shift of 0.025.

the beam current and β^*) at constant instantaneous luminosity. This scheme would require a cycling full-energy injector.

If the beam current is limited by synchrotron radiation and cryogenic capacity, energy-luminosity levelling would be an intriguing possibility, that is, increasing the collision energy in steps, while the beam current decreases [15]. The energy-levelled luminosity would vary as $L \propto 1/E_b^3$.

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